Stability Study of ac Voltage Source using Josephson Voltage Standards

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***Abstract* — The stability of an ac voltage source fabricated at the National Research Council Canada (NRC) is investigated. In this work, differential sampling was used to monitor the source voltage with respect to a step-wise approximated reference waveform generated by the Programmable Josephson Voltage Standard (PJVS) at 4 V and at 1 V. The frequency dependence of the source error is extracted, and the same measurements are repeated 13.5 months later to determine the long-term stability. Different digitizers are used to evaluate input filter effects. The NRC ac voltage source is found to be a suitable travelling standard with a stability of < 4 µV/V per year. At the National Institute of Standards and Technology (NIST), differential sampling was used to monitor the difference between a Josephson Arbitrary Waveform Synthesizer (JAWS) at 1 V and this source. Information is obtained about the effect of relative humidity on the source phase.**

***Index Terms* — Josephson effect, digital sampling, voltage measurement, voltage fluctuations, humidity dependence.**

I. Introduction

NRC has recently made new developments in digital sampling and in ac source fabrication with a goal to provide ac voltage traceability directly to Josephson voltage standards [1] – [4]. The NRC ac source characteristics have previously been determined at 4 V and 1 kHz as follows: stability was 0.057 µV/V over 3 days, the Allan deviation was 17 nV/V at an averaging period of 1.7 h, and the temperature coefficient was 0.05 µV/V/ºC [4]. These results demonstrated the potential for this ac source to be used as a travelling standard; however, its long-term stability remained unknown. Here, we present differential sampling measurement results acquired at NRC 13.5 months apart to quantify the long-term stability of the NRC ac source as well as the influence of voltage, frequency, and choice of digitizer. The source is also measured by NIST, where additional short-term stability information is gathered along with an estimation of the dependence of phase on relative humidity.

II. NRC Results

At NRC, a Programmable Josephson Voltage Standard (PJVS) provides the reference step-wise approximated waveform that the NRC ac source is compared to in differential sampling. PJVS quantization is ensured by measuring PJVS current margin tables daily, performing dither current quantum locking range measurements at the beginning and at the end of calibrations, and performing checks with ± 0.5 mA dither current through the PJVS while it generates ac waveforms before and after each ac calibration run. The phase of the source is aligned iteratively with that of the PJVS by briefly offsetting the clock frequency of the source. The nominal amplitude setting of the ac source is also adjusted iteratively to reduce the difference in signals between the source and the PJVS.

Figure 1 shows the ac source error, Δ, obtained for various frequencies at an rms amplitude of 4 V using a modified Keysight 3458A[1] as a sampling digital voltmeter (SDVM). The modification extracts its 10 MHz reference signal. Above 100 Hz, the source displays a larger error. The exact frequency cutoff of the sampling Keysight 3458A input is not known well, although it should be near 144 kHz [5]. A correction is applied in Fig. 1 for this effect, for the finite aperture, and for the 20 kHz nominal roll-off of the source anti-aliasing filter.

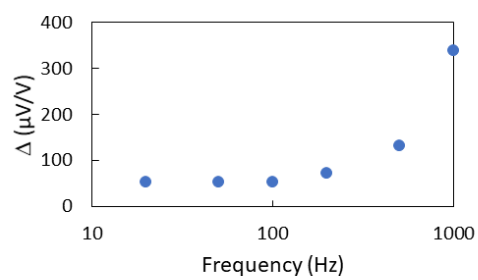

Fig. 1. Ac source error, Δ, as a function of frequency at 4 V as measured by differential sampling with the Keysight 3458A in October 2022 against the NRC PJVS. Δ is calculated as the relative difference between the measured fundamental amplitude as extracted by Fast Fourier Transform (taking into account the SDVM input filter and the finite aperture) and the nominal source amplitude (taking into account the value of the external dc reference and the nominal roll-off of the source anti-aliasing filter).

Given the large source error above 100 Hz, switching to a different SDVM may be advantageous [5]. For instance, the Fluke 8588A[1] has a much larger input frequency cutoff, so corresponding corrections should become small. Table 1

[1] Certain commercial instruments are identified in this paper to facilitate understanding. Such identification does not imply recommendation or endorsement by NRC or NIST, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.

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summarizes results at 100 Hz and 1 kHz, when using the Keysight 3458A and the Fluke 8588A SDVMs at two different voltages. Agreement within 0.5 μV/V is found between source errors at 1 V and 100 Hz with Fluke 8588A and 4 V and 100 Hz with Keysight 3458A, showing the ac source has both excellent linearity and long-term stability at 100 Hz. For the Fluke 8588A at 1 kHz, the change from 1 V to 4 V is 1.6 μV/V. Results at 4 V and 1 kHz with the Keysight 3458A obtained 13.5 months apart differ by 4.1 μV/V, consistent with a long-term stability of 3.7 μV/V per year at that frequency. The large 16 μV/V difference at 4 V and 1 kHz when using different SDVMs is ascribed to an incomplete characterization of the Keysight 3458A input filter.

Table 1. Ac source error in various conditions of voltage and frequency settings over time and with different SDVMs.

Date	Voltage (V)	SDVM	Ac source error (μV/V)	
			100 Hz	1000 Hz
Oct 2022	4	3458A	54.9	339.6
Nov 2023	4	3458A	N/A	335.5
Nov 2023	4	8588A	N/A	351.0
Nov 2023	1	8588A	54.4	349.4

III. NIST Results

At NIST, the Josephson Arbitrary Waveform Synthesizer (JAWS) is set to generate a reference sine wave at 1 V and a frequency of 1 kHz or 100 Hz. The JAWS waveform is synchronized with a trigger signal from the NRC ac source, and its phase is adjusted to minimize the voltage difference between the JAWS and the NRC source, labeled “differential voltage” in Fig. 2. The differential voltage is measured by a Zurich Instruments MLFI[1] digitizer. The NRC source rms amplitude is manually adjusted for each frequency to be near 1 V (at ~14 % of its full-scale amplitude). Results of the rms differential voltage (amplitude and phase), along with the laboratory's relative humidity (RH), are shown as a function of time in Fig. 2.

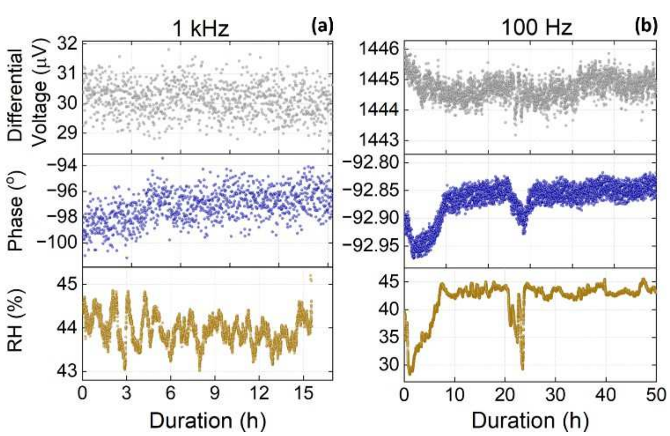

Fig. 2. Differential rms voltage amplitude and phase between the JAWS and the NRC ac source and the relative humidity recorded at NIST for a 1 V sine wave at a) 1 kHz and b) 100 Hz.

In Fig. 2a, the rms voltage evolution at 1 kHz and RH ~44 % is remarkably stable over 16 h. Allan deviation plots (not shown) reveal that ~30 min of averaging is enough to reach the 0.1 μV/V level before drift starts having an effect.

Results of measurements acquired at a frequency of 100 Hz over 51 h are shown in Fig. 2b. After manual adjustment, differential voltage shown at the top of Fig. 2b is still rather large, because there were fewer adjustment iterations at 100 Hz compared to 1 kHz. Knowing both the phase of the 1 V JAWS waveform at 100 Hz and its amplitude from a separate measurement with the digitizer (not shown), the amplitude and phase of the ac source can be reconstructed from the data in the top two panels of Fig. 2b. The ac source rms amplitude is 0.998 557 98 V ± 0.37 μV. Its phase is $(-89.432\ 654 \pm 46\times10^{-6})$ °. Both uncertainties have a coverage factor of $k = 1$. While the phase of the differential signal at 100 Hz (Fig. 2b, center plot) shows a ~0.15° peak-to-peak fluctuation with time, the reconstructed source phase, with the null measurement technique, varies less than 0.0002° and is anti-correlated with the RH measurement. From the phase evolution, the RH coefficient is -1×10^{-5} °/%. This could arise from a small change in the capacitance of the source filter. The reconstructed source amplitude (not shown) does not have as strong a correlation with RH. A benefit of using a JAWS as a reference is the enhanced phase sensitivity, mainly from the reduced differential voltage amplitude (free of transients), compared to the PJVS differential sampling method.

IV. Conclusion

In summary, the ac voltage source fabricated by NRC can be used as a travelling standard with a stability uncertainty of 3.7 μV/V per year as demonstrated by measurements performed at NRC 13.5 months apart. Differential sampling results at 1 V and 4 V showed the source is linear on the order of a part per million, but that the characterization of SDVM input frequency cutoff is crucial. At NIST, a dependence of the source phase on RH was observed. This ac source is promising for use as an ac voltage standard, and it also could be used as a transfer standard in upcoming on-site comparisons of ac voltage.

References

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